

## Stockpile Stewardship and Nuclear Science with GEANIE at LANSCE/WNR

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GEANIE (for Germanium Array for Neutron-Induced Excitations) is a large, escape-suppressed germanium detector array in the Weapons Neutron Research (WNR) facility at the Los Alamos Neutron Science Center (LANSCE). The use of GEANIE with the intense, pulsed, white source of neutrons at LANSCE/WNR<sup>1</sup> provides new and powerful capabilities for Science-Based Stockpile Stewardship (SBSS) and nuclear science. The acquisition, installation, operation, and use of the array is a major collaborative effort between researchers from Lawrence Livermore National Laboratory and Los Alamos National Laboratory. The primary goal of the collaboration is to determine the  $^{239}\text{Pu}(n,2n)$  cross section to an accuracy of  $\pm 10\%$ . Other important nuclear data needs are also being addressed. The unique combination of a high-resolution gamma-ray ( $\gamma$ -ray) spectrometer with a high-energy neutron source provides exciting opportunities in nuclear physics as well.

Advances in the technology of germanium-detector fabrication and in accelerator technology have enabled major advances in nuclear physics. In the past, these improvements have focused on nuclear-structure physics with large arrays of escape-suppressed germanium detectors used at accelerator facilities with heavy-ion beams. The important characteristics of such arrays for nuclear spectroscopy are high energy resolution (1/1000), good efficiency, escape suppression for background reduction, and high granularity. Perhaps the best known physics from these arrays is the discovery of superdeformed bands.<sup>2,3</sup>

The development and use of GEANIE at LANSCE/WNR creates a powerful new tool for SBSS. The use of a spallation neutron source makes it possible to simultaneously measure excitation functions over a wide energy range. At full power, the WNR spallation source is the most intense high-energy neutron source in the world. This is the first time that a large  $\gamma$ -ray detector array has been used at a neutron spallation source. This unique combination opens up new possibilities for research in areas of nuclear excitation that previously have been difficult to access.

Measuring characteristic  $\gamma$  rays that follow neutron-induced reactions usually allows the determination of both the reaction channel—for example,  $(n,2n)$  or  $(n,3n)$ —and the particular level excited in the product nucleus. In addition, the reaction thresholds and cross-section peaks observed in excitation functions provide valuable information for the identification and study of the various reaction products. Because of the high neutron energies available, many different reactions are possible. A short list includes the following:  $(n,n'\gamma)$ ,  $(n,xn\gamma)$  [where  $x = 2, 3, 4, \dots$ ],  $(n,p\gamma)$ ,  $(n,np\gamma)$ ,  $(n,a\gamma)$ , and  $(n,na\gamma)$ .

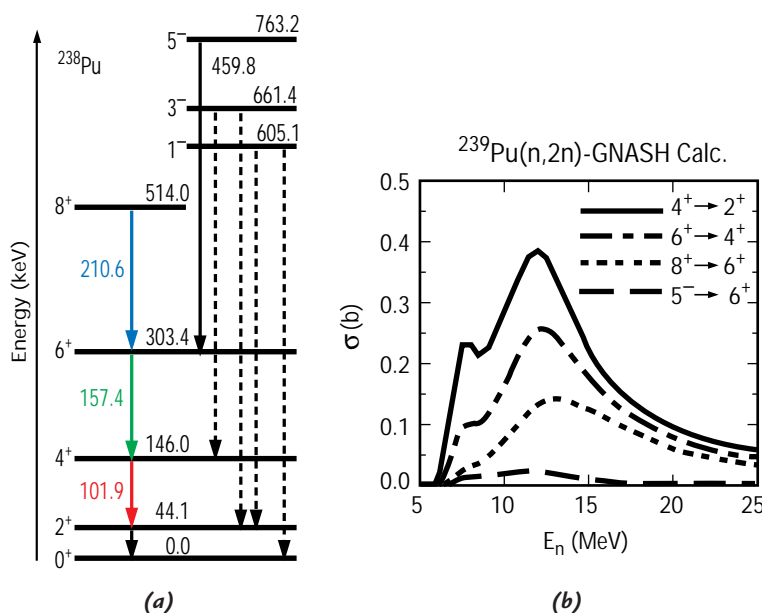


Fig. II-15. (a) Level scheme showing the ground-state rotational band and negative parity band in  $^{238}\text{Pu}$ . (b) The GNASH-calculated values of the cross sections of these lines as a function of neutron energy.

An accurate measurement of the  $^{239}\text{Pu}(n,2n)^{238}\text{Pu}$  reaction cross section is needed to better understand the radiochemical data from past Nevada Test Site experiments. From measured  $\gamma$ -ray production cross sections, we obtain an estimate of total reaction cross sections as a function of incident neutron energy. By combining our results with calculations from the coupled preequilibrium and Hauser-Feshbach computer program GNASH,<sup>4</sup> we can use theory to account for the fraction of the cross section that is not measured with our technique. Figure II-15 shows GNASH values for the excitation functions of some of the  $\gamma$  rays in  $^{238}\text{Pu}$  resulting from the  $^{239}\text{Pu}(n,2n)$  reaction. In Fig. II-16 we show the GNASH-predicted cross-section ratios of  $(n,2n\gamma)$  to  $(n,2n)$  for some of the stronger transitions. The ability to simultaneously measure excitation functions for many  $\gamma$ -ray transitions provides numerous checks for validation of the data and of the models used in the GNASH code.

Because a large fraction of the  $\gamma$ -ray cascade populates the lowest-lying states in the product nucleus, the cross sections for the decay of the low-lying states provide the best measure of the total reaction cross section. A limitation of this technique occurs for very low energy states, such as the first excited state in  $^{238}\text{Pu}$  at 44 keV above the ground state. Very-low-energy  $\gamma$ -rays are highly internally converted (emitting an electron) as well as being highly attenuated in the sample, making these transitions difficult to observe. This technique of determining the reaction cross section from the partial  $\gamma$ -ray cross section can be used for  $E_\gamma > 100$  keV. It provides a means to study nuclei via  $(n,xn)$  reactions (where  $x = 1, 2, 3, \dots$ ), probing nuclei that are otherwise difficult to access. Our previous experiments<sup>5</sup> with a single unsuppressed germanium detector, in which we observed reactions on  $^{208}\text{Pb}$  up to  $(n,9n)$ , laid much of the

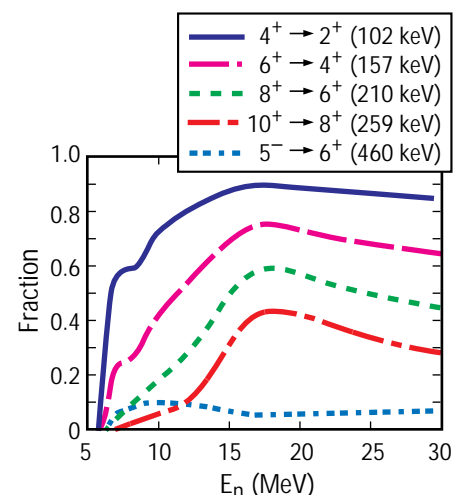
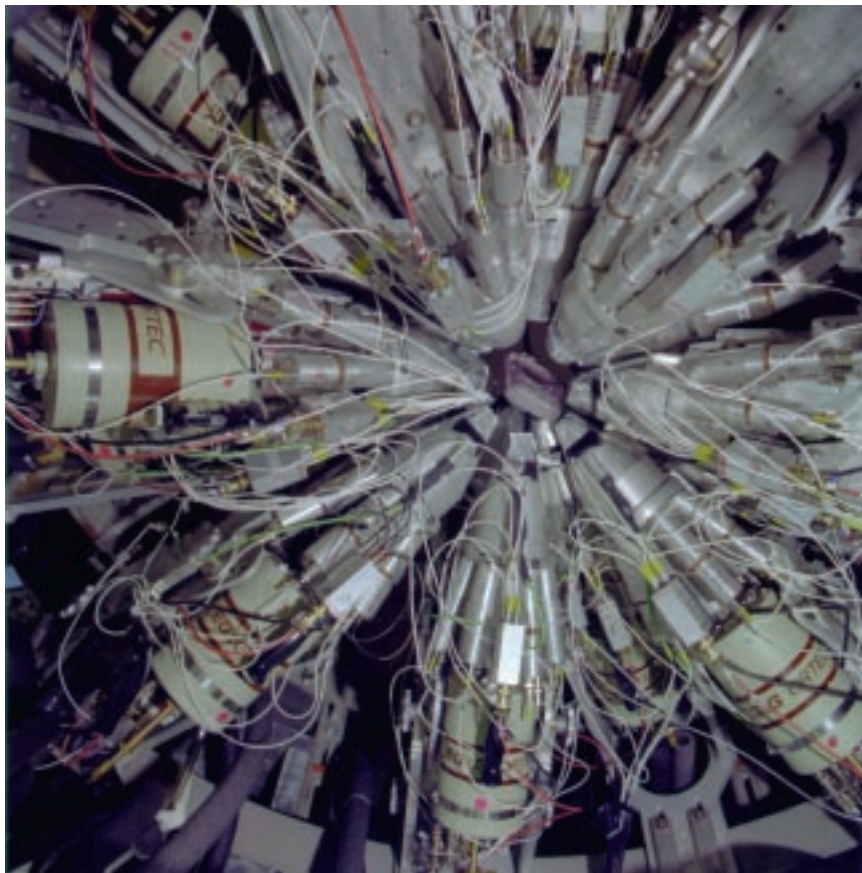


Fig. II-16. Cross-section ratios from GNASH calculated values. The  $4^+$ -to- $2^+$  transition has over 70% of the total reaction cross section for  $E_n > 10$  MeV.



*Fig. II-17. Photograph of GEANIE.*

groundwork for applying this technique to actinides. The innovation of using planar germanium detectors was important for successful actinide studies, too.

GEANIE presently consists of 20 bismuth germanate (BGO) escape-suppression shields surrounding 20 germanium detectors. Figure II-17 is a photograph of the detector array. GEANIE was built using elements of the High-Energy-Resolution Array (HERA),<sup>6</sup> which was developed by the Nuclear Structure group at Lawrence Berkeley National Laboratory. GEANIE is located 20 m from the production target on a neutron flight path that is 60° to the incident proton beam.

Of the 20 escape-suppressed germanium detectors, 7 have planar geometry and the remaining 13 are coaxial. The coaxial detectors are 25% efficient

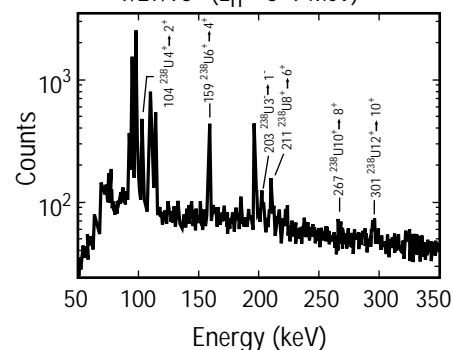
relative to a 3-in.  $\times$  3-in. NaI(Tl) detector. The BGO escape-suppression shields improve the peak-to-total ratio for the coaxial detectors from  $\sim 0.15$  to  $\sim 0.45$  for a 1.33-MeV  $\gamma$  ray. All of the germanium detectors are interchangeable within the suppression shields, and the efficiency of the array is on the order of 1% for the full absorption peak of a 1.33-MeV  $\gamma$  ray. Short-term plans call for adding six more unsuppressed germanium detectors to the array. The long-term goal is to operate the array with a total of 30 suppressed germanium detectors, 10 planar and 20 coaxial.

Timing and energy resolution are equally important in our experiments. The timing resolution of the germanium detectors is important because we use it to deduce the incident neutron energy based on the time of flight. Optimal energy resolution is always important in resolving closely spaced  $\gamma$  rays, but this is particularly true for experiments with actinide samples that have closely spaced nuclear levels and numerous  $\gamma$ -decay transitions. The planar germanium detectors produce higher timing and energy resolution than the coaxial detectors, and the planar detectors also have lower background rates from the scattered neutrons because of their thin geometry. The limitation of the planar detectors is their reduced efficiency at higher  $\gamma$ -ray energies. A combination of both coaxial and planar germanium detectors provides a powerful spectrometer for a wide range of experiments. The useful energy range for the coaxial germanium detectors extends from  $\sim 50$  keV to over 5 MeV. The corresponding range for the planar detectors is from  $\sim 30$  keV to over 500 keV.

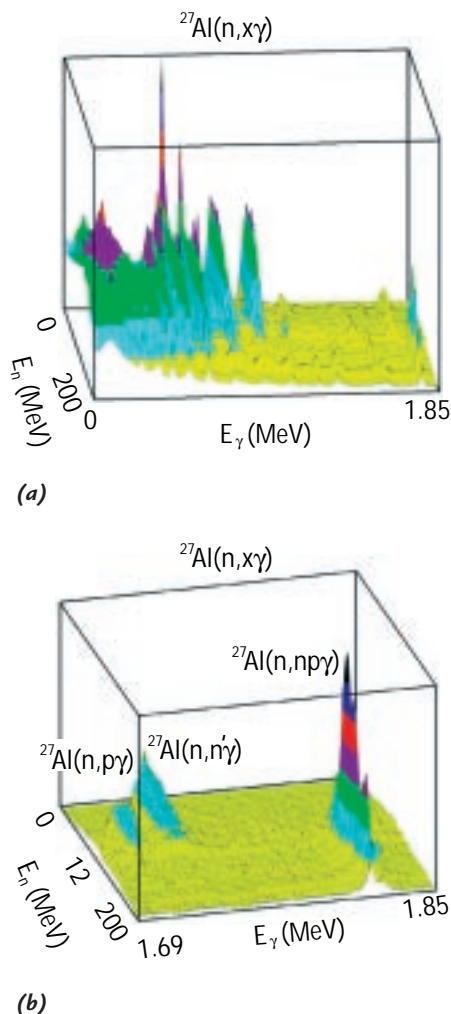
The data that we acquired include single  $\gamma$ -ray events as well as  $\gamma$ - $\gamma$  coincidences. Both types of data can be used to deduce cross sections, and the coincidence data permit more detailed spectroscopy to be undertaken. The coincidence data enable background reduction that helps in observing less intense  $\gamma$ -ray lines. Our data-acquisition system is based on the  $4\pi$  array system at Michigan State University.

The use of  $\gamma$  rays is an important tool for  $(n, xn)$  measurements on actinide nuclei because the production of neutrons from fission interferes with a direct measurement of the  $(n, xn)$  neutrons. The good peak-to-total ratio of the GEANIE detectors allows the resolution of individual  $\gamma$ -ray lines above the background from fission and other  $\gamma$  rays. The planar detectors play an especially important role in these measurements because they have excellent energy resolution and are relatively insensitive to neutrons. This is the first time that multiple planar germanium detectors have been used to study actinide nuclei. Figure II-18 shows a planar detector spectrum from a  $^{238}\text{U}$  sample. The uranium x-rays and the first  $4^+$ -to- $2^+$  excited-state  $\gamma$ -ray transition are clearly visible. The observation of this low-energy transition makes possible an accurate measurement of the  $(n, 2n)$  cross section.

GEANIE LEPS with Compton Suppression  
9/27/96 ( $E_n = 5\text{--}9$  MeV)



**Fig. II-18. Spectrum from planar germanium detectors showing the  $4^+$ -to- $2^+$  transition located between large x-ray peaks. Gamma rays from higher-lying levels are indicated as well. These data are for neutron energies between 5 and 9 MeV.**



**Fig. II-19. (a) Gamma-ray data from  $^{27}\text{Al}(n, x\gamma)$ . The “ridges” are yields from various  $\gamma$ -ray transitions. (b) Detail of part of the data in (a) showing peaks from three different reactions, inelastic scattering,  $(n, p\gamma)$ , and  $(n, np\gamma)$ .**

We designed special  $^{239}\text{Pu}$  samples encapsulated in a frame with thin beryllium windows to allow good low-energy  $\gamma$ -ray transmission. The design, fabrication, and use of these samples required a major effort. Using these samples, we have acquired data and observed the  $6^+$ -to- $4^+$  and other transitions in  $^{238}\text{Pu}$ . The radioactive decay of the plutonium makes data acquisition and background reduction challenging. The initial data reduction has been started, and further data will be acquired during the LANSCE accelerator operating period in 1997.

GEANIE at WNR offers an opportunity for complete spectroscopy in regions of angular momentum and excitation that are inaccessible with other neutron sources or with charged-particle beams. Such studies allow detailed tests of nuclear-structure models and level-density parameterizations. Neutron inelastic scattering is expected to be an especially valuable reaction for complete spectroscopy because it tends to populate all levels within the constraints of the angular momentum imparted to the nucleus. Data taken with an  $^{27}\text{Al}$  sample that were collected in a brief run in November 1996 show the power of GEANIE/WNR to investigate nuclear excitations. A three-dimensional spectrum from the  $^{27}\text{Al}(n, x\gamma)$  single-event data is shown in Fig. II-19. Gamma rays produced by neutrons with energies from 1 to 200 MeV can be seen as ridges in part (a) of Fig. II-19. This plot shows one-half of the  $\gamma$ -ray energy range measured in the experiment. Part (b) of Fig. II-19 shows a small section of the data from part (a). In this region,  $\gamma$ -rays from  $(n, n'\gamma)$ ,  $(n, p\gamma)$ , and  $(n, np\gamma)$  reactions are visible. The incident neutron energies at which these reactions are energetically allowed are all different, as can be seen by the different points along the  $E_n$  axis at which the “ridges” first occur.

From a brief run on a  $^{196}\text{Pt}$  target we observed the  $^{196}\text{Pt}(n, 15n\gamma)$  reaction. This is the highest neutron multiplicity we have seen yet and demonstrates the potential for reaching neutron-deficient nuclei.

A sampling of the physics that will be pursued at GEANIE is contained in the objectives of proposals submitted to the December 1996 LANSCE Program Advisory Committee. The proposals included a search for rigid triaxial motion, an investigation of single-particle vibrational interactions in rare-earth nuclei, level-density studies, an exploration of exotic neutron-deficient nuclei, a verification of the double octupole phonon in  $^{208}\text{Pb}$ , a search for intermediate states in  $^{180}\text{Ta}$  to explain its cosmic abundance, and a study of the level statistics in  $^{27}\text{Al}$ . Another proposal is to measure the  $\text{Lu}(n, xn)$  reaction cross sections for use as a diagnostic in experiments related to Accelerator Production of Tritium (APT). Off-line experiments with GEANIE are planned for times when the accelerator is not in operation. GEANIE is an important asset for stockpile stewardship and is attracting outstanding researchers because of the research opportunities available.

## References

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